Compound TiO_2 Interlayers for the Novel Witricity Charger with FEM Simulations and Corresponding Experiments

Junhua Wang[1, 2], S. L. Ho[1], W. N. Fu[1], Mingui Sun[2], and Jianguo Zhu[3]

[1]Department of Electrical Engineering, The Hong Kong Polytechnic University, Hong Kong
[2]Department of Neurological Surgery, University of Pittsburgh, Pittsburgh, PA, USA
[3]Faculty of Engineering and Information Technology, University of Technology, Sydney, NSW, Australia
junhua.wong@polyu.edu.hk

Abstract —A non-radiative energy transformer with TiO_2 nano-powder and $(C_4H_6O_2)_x$ latex combined interlayer, working on 'strong coupling' between two coils, which are physically separated from each other by distances that are longer than the characteristic sizes of each resonator, is proposed to realize efficient wireless energy transfer. Non-radiative energy transfer between the two resonators is facilitated through the coupling of their resonant-field evanescent tails. Corresponding finite element analysis (FEA) and experiments have been carried out to facilitate quantitative comparison. The analysis reported allows a formal design procedure to be established for optimization of Witricity transfer for a given application.

I. INTRODUCTION

In both traditional magnetic coupling and advance Witricity systems for implantable devices, the transmitter and receiver coils are separated by a layer of skin and tissue, in the range of 1 cm to 5 cm. The coils are usually misaligned, due to anatomical constraints and hence the coupling efficiency is inevitably impaired. For traditional magnetic coupling systems [1-4], low power inductive links are characterized by very unfavorable coil coupling conditions to result in large coil separation or a very small pickup coil diameter. The coupling factor can be as low as l % and may vary in a very unpredictable manner due to coil misalignments. But for Witricity systems [5], the resonant nature of the process ensures that the interaction between the source and device is sufficiently strong and the interaction with non-resonant objects is minimal. In this manner, an efficient wireless channel for power transmission can be established and the efficiency is up to 60%-90% with a distance of about 1-5 cm between the transmitter and the receiver.

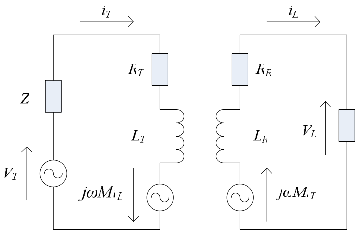
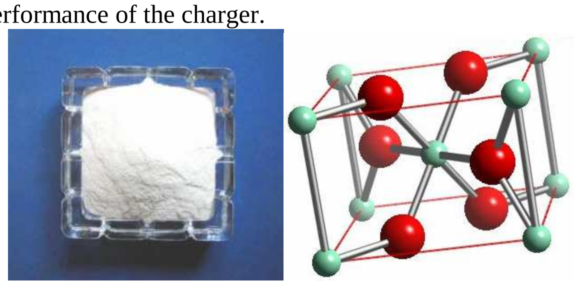


Fig. 1. Equivalent circuit for the inductive link representing the two resonant coils.

As the present Witricity works at the MHz range, some undesirable problems become inevitable. First is that high frequency devices are much more expensive than their low frequency counterparts. High-frequency circuits and digital circuits are often sharing the same circuit board, constituting the so-called mixed signals or cross talks. High-frequency circuits are sometimes unstable as the digital circuits start up as the noise generated by the digital circuit affects the normal actions of high frequency circuits. Also, realization of inductive charging at high frequencies in electrical devices results in relatively more radiation and quick heat generation. An equivalent circuit for a Witricity system is presented in Fig. 1.

In this paper, a novel Witricity charger with TiO_2 nano-powder and $(C_4H_6O_2)_x$ latex combined interlayer is proposed. Finite element analysis (FEA) and corresponding experiments have also been carried out to showcase the performance of the charger.



(a) (b)

Fig. 2. (a) TiO_2 nano-powder material; (b) The structural model of rutile TiO_2.

II. PREPARATION OF TiO_2 COMPOUND INTERLAYERS

Titanium exists in a number of crystalline forms and the most common two are anatase and rutile. Pure titanium dioxide does not occur in nature but can be derived from ilmenite or leuxocene ores. Fig. 2 (a) and (b) shows the photos of rutile TiO_2 nano-powder material and its structural model. Because of the relatively poor mechanical properties, applications using sintered titania are limited.

For the proposed Witricity system, the effective inductance L and the effective capacitance C for each coil can be defined as follows [5]

$$L = \frac{\mu_0}{4\pi|I_0|}\iint d\mathbf{r}d\mathbf{r}'\frac{\mathbf{J}(\mathbf{r})\cdot\mathbf{J}(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|} \tag{1}$$

$$\frac{1}{C} = \frac{1}{4\pi\varepsilon_0|q_0|^2}\iint d\mathbf{r}d\mathbf{r}'\frac{\rho(\mathbf{r})\cdot\rho(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|} \tag{2}$$

where $\mathbf{J}(\mathbf{r})$ is the spatial current and $\rho(\mathbf{r})$ is the charge densities. Then the energy W contained in the coil can be deduced by

$$W = \frac{1}{2}L|I_0|^2 = \frac{1}{2C}|q_0|^2 \tag{3}$$

Based on this relation and the equation of continuity, the resulting resonant frequency is

$$f_0 = 1/\left[2\pi(LC)^{1/2}\right] \tag{4}$$

And the coil can be treated as a standard oscillator in coupled mode theory by defining

$$a(t) = 1/\left[(LC)^{1/2}\right] I_0(t) \tag{5}$$

According to the equation (1)-(5), the resonant frequency of the proposed Witricity system and other Witricity systems, also known as eigenfrequency, is determined by the following equations:

$$\omega_{trans} = 1/\sqrt{L_{trans} C_{trans}} \tag{6}$$

$$\omega_{rec} = 1/\sqrt{L_{rec} C_{rec}} \tag{7}$$

where L_{trans} and C_{trans} are the transmitter coil's total inductance and total capacitance, respectively; L_{rec} and C_{rec} are the receiver coil's total inductance and total capacitance, respectively.

It can be seen from equations (6) and (7) that the resonant frequency will decrease by tuning the capacitance down. And through selecting materials with high permittivity, the capacitance can be increased. Based on that condition, new interlayers consisting of 99.9% TiO_2 nano-powder and $(C_4H_6O_2)_x$ latex is fabricated. As the compound material is composed of TiO_2 nano-powder and $(C_4H_6O_2)_x$ latex, it offers significant advantages over conventional dielectric materials. As it is boned with high-purity TiO_2 nano-powder, it has a quite high permittivity and this is needed for lowering the systems' eigenfrequency.

III. FEM Simulation Results and Experiment Results

In order to uphold the performance of the proposed system, an interpolative FEA modeling method is introduced in this paper. The charger has a relatively high electric field when compared with those of the traditional magnetic coupling devices at the resonant frequency of 612 kHz at which efficient energy transfer is expected to occur in the proposed charger. At that point, most of the energy is transferred from the primary coil to the secondary coil. Fig. 3 shows the receiver output voltage (with a distance of 5 cm) versus frequencies for the proposed Witricity system, the Witricity charger and the traditional one. It can be seen that the induced voltage of the proposed charger has a peak value, i.e. 153 V at a frequency of about 621 kHz and that of the Witricity charger is 171 V at a frequency of about 4.08 MHz. Voltages of the traditional magnetic coupling model only increase slightly when the frequency rises.

The designed resonant frequency should be low at about 300 kHz if the thickness of TiO_2 combined interlayer is the same with the non-TiO_2 interlayer, but it is impossible in practice due to the limitation of the mechanical process.

Based on the design experience of Witricity chargers, a noval charger is prepared using laboratory means with the same size of transmitter and receiver. It can be seen from Fig. 4 that if the traditional inductive coupling method is used, the physical separation distance must be limited to less than 2 cm in order to realize the similar efficiency of Witricity system with about a 15 cm distance. The studies indicate that the proposed Witricity system is a suitable and practical technology for providing wireless power to charge a wealth of electrical devices, especially over relative large distance and slightly variable frequencies.

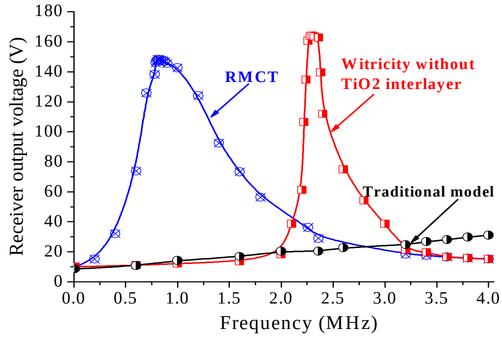


Fig. 3. Receiver output voltage vs. frequency with a distance of 5 cm.

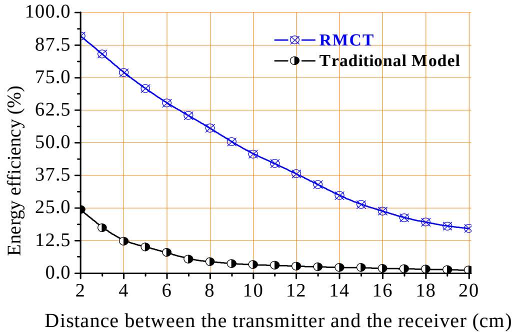


Fig. 4. Efficiency comparison between the propose Witricity charger and the traditional magnetic coupling charger.

IV. Conclusion

New interlayers with high relative permittivity, produced by combined TiO_2 nano-powder and $(C_4H_6O_2)_x$ latex, is proposed in this paper to design a novel resonant inductive magnetic coupling wireless charger. The proposed Witricity charger has been analyzed by employing FEM analysis and the findings are validated experimentally. Operating resonant frequency, output voltage, current, power and the transfer efficiency are studied at different frequencies and distances between the primary coil and the secondary coil.

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